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Maximum usable strain of FRP-confined concrete

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HIGHLIGHTS

- Usable strain of FRP-confined concrete.
- Progressive failure mechanisms of FRP-confined concrete.
- Residual strength of FRP-confined concrete columns.

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ABSTRACT

This study investigates the progressive failure of FRP-confined concrete. Ten FRP-confined concrete specimens were divided into two groups with different jacket stiffness. One specimen in each group was tested until failure while the others were loaded to target strains and then unloaded in order to monitor the residual strength of the concrete cores. At 1% axial strain of FRP-confined concrete, the residual strength of the concrete cores were reduced more than 56% compared to the reference specimens. Experimental results have shown that the maximum usable strain of 1% is unconservative for FRP-confined concrete. A model is proposed to estimate the residual strength of concrete cores. Predictions from the proposed model fit the experimental results well. In addition, a new procedure is proposed to determine the maximum usable strain of FRP-confined concrete based on the maximum usable strain of unconfined concrete.

1. Introduction

Fibre Reinforced Polymer (FRP) has been commonly used to strengthen existing reinforced concrete (RC) columns in recent years [1–3]. In such cases, FRP is a confining material for concrete in which the confinement effect leads to increase the strength and ductility of columns. In early experimental studies of FRP retrofitted RC columns, the axial capacities of strengthened columns increased significantly as compared to reference columns. The database collected by Lee and Hegemier [4] showed that FRP-confined concrete cylinders have maximum compressive strain ranging from 0.6% to 4.2% while Teng et al. [5] showed that the maximum compressive strain of specimens varied from 0.8% to 3.7%. Pham and Hadi [6] collected a database of 167 FRP-confined concrete columns where the maximum compressive strain of the columns ranged between 0.5% and 4%. Ilki et al. [7] conducted experiments on FRP-confined circular and rectangular RC columns. Results from this study had shown that the maximum compressive strain of FRP-confined concrete ranged from 1.3% to 8.6%. The maximum compressive strain up to 9.66% was recorded from the experimental study carried out by Dai et al. [8] on RC columns confined with large rupture strain and the maximum compressive strain up to 10.4% was reached in Ilki et al.'s study [9] on FRP confined low strength concrete members. From the literature, it can be seen that the maximum compressive strain of FRP-confined concrete varies in a broad range and no study has shown a maximum usable strain of confined concrete [10–14]. Meanwhile, ACI-440.2R [15] and The Concrete Society [16] provided maximum usable strain of 1% for FRP-confined concrete to prevent excessive cracking and the resulting loss of concrete integrity.

In addition, ACI-440.2R [15] defines the maximum usable strain of unconfined concrete. However, there is no definition for maximum usable strain of confined concrete in ACI-440.2R [15]. As mentioned above, experimental studies have shown that the maximum compressive strain of FRP-confined concrete varies in a wide

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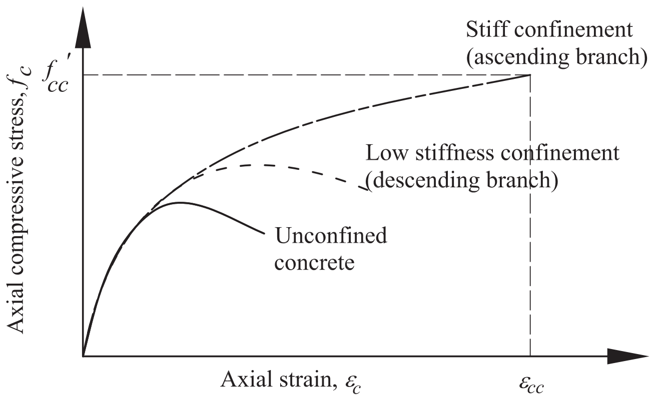

Fig. 1. Stress–strain relation of concrete.

range from 0.5% to 10.4%. However, these studies did not investigate the integrity of the concrete during testing. No study has investigated the precise nature of the progressive failure mechanisms occurring during experimental tests. In other words, a limit of 1% for maximum compressive strain for confined concrete recommended by the two guidelines [15,16] seems small as compared to the experimental results. Therefore, determining the nature of the progressive failure mechanisms and the maximum usable strain of FRP-confined concrete is essentially necessary. This study conducted experimental tests to investigate the progressive failure mechanisms of FRP-confined concrete at many stages of testing.

2. Axial strain of concrete

A typical stress–strain relation of unconfined concrete is shown in Fig. 1. The stress–strain curve rises to a maximum stress, reached at a strain between 0.15% and 0.3%, followed by a descending branch [17]. The length of the descending branch of the curve is strongly affected by the test conditions. Usually, an axially loaded concrete cylinder fails at the maximum stress. In such cases, the stress–strain curve suddenly drops from the maximum stress. On the other hand, if a structural member is loaded in compression due to bending (or bending plus axial load), the descending branch might exist as shown in the solid line after the maximum stress in Fig. 1 [17]. This study deals with pure compression tests so that the failure of unconfined concrete is approximately determined at the maximum stress stage that has a corresponding strain between 0.15% and 0.3%.

In addition, stress–strain relations of FRP-confined concrete are also presented in Fig. 1. Based on the confinement ratio, the stress–strain relation of FRP-confined concrete may belong to an ascending branch or a descending branch. Specimens with low stiffness confinement yield a descending branch stress–strain curve as described by The Concrete Society [16]. The axial stress of these specimens reaches the maximum stress before FRP rupture. Conversely, the axial stress of specimens that have stiff confinement reaches the maximum stress at the FRP rupture. Therefore, the maximum compressive strain of FRP-confined concrete is the measured axial strain of specimens as FRP ruptures due to tension forces in hoop direction. There is a consensus that the core of FRP-confined concrete can resist the applied load until FRP ruptured without any investigation about the progressive failure mechanisms. No study about confined concrete has verified the integrity of the concrete core during testing. As a result, the failure indicator of FRP-confined concrete is controlled by the failure of the FRP jacket. This failure determination complies with the failure definition of concrete confined by helical steel reinforcement [18]. Mander et al. [18] defined that the maximum axial strain of confined concrete was reached when the first lateral reinforcement fractures. However, this study focuses on the failure of the concrete cores not the FRP.

3. Experimental program

3.1. Design of experiments

A total of thirteen standard concrete cylinders were cast and tested at the High Bay laboratory of the University of Wollongong. The dimensions of the specimens were 150 mm by 300 mm and the design compressive strength of concrete was 50 MPa. The specimens were classified into three groups, namely, the reference group (R), two layers group (C2) and three layers group (C3). Details of the specimens are presented in Table 1. The notation of the specimens consists of two parts: the first part is "R", "C2", and "C3" stating the name of the groups. The second part indicates the target strains of the specimens at which the loading was stopped. For example, Specimen C2-1.9 indicates the specimen which was wrapped with two layers of FRP and loaded up to 1.9% axial strain.

After 28 days, each specimen was symmetrically bonded at midheight with two 60 mm strain gages in the vertical direction and two 60 mm strain gages in the horizontal direction. The specimens on group C2 and C3 were then fully wrapped with carbon FRP (CFRP) layers using a wet lay-up method. The adhesive was a mixture of epoxy resin and hardener at 5:1 ratio and the amount of FRP layers in the specimens is described in Table 1. For each specimen, four CFRP rings of 75 mm width were applied in the hoop direction to ensure that the whole specimen (300 mm length) was wrapped with layers of CFRP. Before the first layer of CFRP was attached, the adhesive was spread onto the surface of the specimen and CFRP was attached onto the surface. After the first layer, the adhesive was spread onto the surface of the first layer of CFRP and the second layer was continuously bonded. The third layer of

Table 1
Test matrix.

ID	Unconfined concrete strength (MPa)	Target axial strain (%)	Actual axial strain (%)	Predicted lateral strain (%)	Actual lateral strain (%)	Predicted strength (MPa)	Actual strength (MPa)	No. of FRP layers
C2-0.6	52	0.6	0.62	0.46	0.44	69	70	2
C2-1.0	52	1.0	1.12	0.77	0.68	80	83	2
C2-1.2	52	1.2	1.33	0.91	0.94	84	89	2
C2-1.4	52	1.4	1.56	1.04	0.92	88	88	2
C2-1.9	52	1.9	1.99	1.25	1.40	95	97	2
C3-0.6	52	0.6	0.66	0.37	0.34	73	77	3
C3-1.0	52	1.0	1.02	0.62	0.67	87	90	3
C3-1.4	52	1.4	1.35	0.83	0.70	98	96	3
C3-1.9	52	1.9	1.87	1.05	1.08	109	106	3
C3-2.4	52	2.4	2.64	1.25	1.31	120	124	3